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RXTE Studies of Cyclotron Lines in Accreting Pulsars

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I INTRODUCTION

Cyclotron lines in accreting X-ray pulsar spectra result from the resonant scattering of X-rays by electrons in Landau orbits on the intense ($\sim 10^{12}$ G) magnetic fields near the neutron star poles. For this reason they are known as cyclotron resonance scattering features (CRSFs). Because Landau transition energies are proportional to field strength ($E_{cyc} = 12$ keV approximately corresponds to $B = 10^{12}$ G), CRSF energies give us our most direct measures of neutron star magnetic fields. Other line properties, such as depths, widths, and presence of multiple harmonics, are strongly dependent on the details of the geometry and environment at the base of the accretion column. CRSFs therefore give us a sensitive (if difficult to interpret) diagnostic of the accretion region.

In this paper, we summarize the *RXTE* measurements of CRSFs in 8 accreting pulsars. The wide bandpass and modest resolution of the *RXTE* instruments make them ideal for measuring these generally broad features. In particular, the high energy response of HEXTE provides a window for discovery of new lines not detectable with proportional counters such as *Ginga* or the PCA alone.

Some highlights of this work are:

- New lines in the well known pulsars Cen X-3 and 4U 1626-67 [**?**,**?**,**?**].
- The discovery of more than two cyclotron line harmonics in 4U 0115+63 [**?**].
- The *RXTE* picture of the correlation between cyclotron line energy and width.

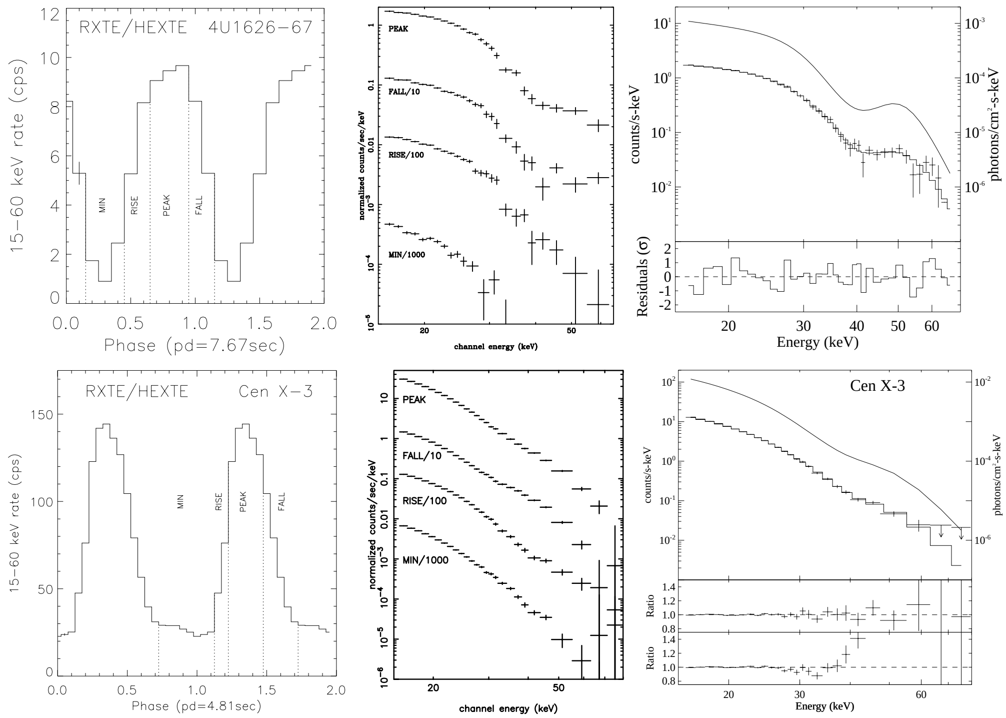

FIGURE 1. *RXTE* observations of (Top) 4U 1626-67 and (Bottom) Cen X-3 . Left: HEXTE light curves folded on the pulse period. Middle: The counts spectra from the four phase intervals. The CRSFs are apparent as inflections in the spectra near 30–40 keV. Right: the inferred incident spectrum from the peak phase, HEXTE count spectrum with model, and ratios to models with (and for Cen X-3 without) a cyclotron line.

II OBSERVATIONS AND ANALYSIS

The results discussed here are based on observations made with the Proportional Counter Array (PCA) [?] and High Energy X-ray Timing Experiment (HEXTE) [?] on board *RXTE*. The PCA is a set of 5 Xenon proportional counters, while HEXTE consists of two arrays of 4 NaI(Tl)/CsI(Na) phoswich scintillation counters. The PCA and HEXTE share a 1° field of view.

Figures 1 and 2 show the measured count spectra together with model fits and inferred incident spectra for eight accreting pulsars. To emphasize the presence of cyclotron lines, residuals to fits made without lines are also shown. In general, these residuals show a dip-like structure at the line energy and then a gross underprediction of the continuum above the line. This is caused by the better statistics on the low side of the feature forcing the model to fit the falling edge of the line. Because no adequate prediction of accreting pulsar continua exists, we employ empirical continuum models. These models (high energy cut-off power law (HECUT), Fermi-Dirac cut-off times a power law (FDCO), and Negative and Positive power law Exponential (NPEX); see [?]) have been successful in fitting pulsars with no cyclotron lines. Only when none

TABLE 1. Summary of *RXTE* Cyclotron Line Measurements. 4U 0115+63 and Vela X-1 require multiple CRSFs in their spectra. The surface B-fields assume a gravitational redshift of 0.3 for the emitting region.

Source	Energy (keV)	Sigma (keV)	Optical Depth	Pulse Phase	Surface B Field (10^{12} G)
4U 0115+63	$12.40^{+0.65}_{-0.35}$	$3.3^{+0.1.9}_{-0.4}$	$0.72^{+0.10}_{-0.17}$	2nd Fall	1.4
	$21.45^{+0.25}_{-0.38}$	$4.5^{+0.7}_{-0.9}$	$1.24^{+0.04}_{-0.06}$	2nd Fall	
	$33.56^{+0.70}_{-0.90}$	$3.8^{+1.5}_{-0.9}$	$1.01^{+0.13}_{-0.14}$	2nd Fall	
4U 1907+09	19.7 ± 0.1	2.6 ± 0.1	0.87 ± 0.05	Average	2.2
4U 1538-52	21.3 ± 0.3	3.05 ± 0.20	0.86 ± 0.07	Average	2.3
Vela X-1	$23.7^{+0.4}_{-0.3}$	5 (fixed)	$0.29^{+0.03}_{-0.04}$	Main Pulse	2.3
	59.7 ± 3.7	12.6 ± 0.8	$1.41^{+0.67}_{-0.61}$	Main Pulse	
Cen X-3	31.8 ± 0.3	7.5 ± 0.9	$0.77^{+0.16}_{-0.11}$	Peak	3.5
GX 301-2	$42.9^{+0.9}_{-2.6}$	$10.0^{+1.9}_{-2.3}$	$0.8^{+0.7}_{-0.3}$	Average	4.8
4U 1626-67	$39.3^{+1.9}_{-1.1}$	6.4 ± 0.8	$2.3^{+0.6}_{-0.4}$	Peak	4.4
Her X-1	41.0 ± 1.0	9.8 ± 0.5	1.84 ± 0.05	Average	4.6

of these continuum models provided an acceptable fit, did we allow cyclotron line(s). We modeled the cyclotron lines with a simple Gaussian optical depth profile.

III RESULTS AND DISCUSSION

Table 1 summarizes the cyclotron line parameters in eight accreting pulsars. In general, pulsar spectra (including line parameters) vary with pulse phase. For this reason, cyclotron lines are often best measured in spectra from limited pulse phase ranges. This is called "pulse phase spectroscopy". Table 1 indicates the phase relative to the pulse profile for which the given parameters apply.

New Lines in Cen X-3 and 4U 1626-67 Cen X-3 and 4U 1626-67 are two of the earliest known accreting pulsars; however, it is only recently that CRSFs were discovered in their spectra [?,?]. Figure 1 shows folded light curves, phase resolved count spectra, and fits to the peak phase spectra. In Cen X-3, the CRSF energy moves by about 20% with phase. This variation has been modeled as resulting from an offset of the magnetic dipole moment from the center of the neutron star [?]. In both sources, the CRSF appears strongest in the "peak" and "fall" spectra. This may also be related to an offset dipole.

4U 0115+63: Multiple Cyclotron Line Harmonics 4U 0115+63 is a transient accreting pulsar in an eccentric orbit with a massive star, a so-called "Be X-ray binary". It was also the first pulsar to show two cyclotron line harmonics [?]. 4U 0115+63 underwent a two month long outburst in 1999 February–April. Observations made with *RXTE* and *Beppo*SAX reveal for

the first time more than two harmonics in a single pulsar [**?**,**?**] (see Fig. 2).
Correlation between Line Energy and Width The width of a CRSF depends on the temperature of the emitting region (kT), the line energy (ω_B) and the viewing angle (θ) with respect to the magnetic field as: $\Delta\omega \propto \omega_B (kT/mc^2)^{1/2} cos\theta$ [**?**]. This predicts that a correlation between line energy and width should exist, provided that viewing angles and plasma temperatures do not vary too greatly from source to source. These *RXTE* results, as well as measurements by *Beppo*SAX [**?**], show a strong correlation, which supports this picture.

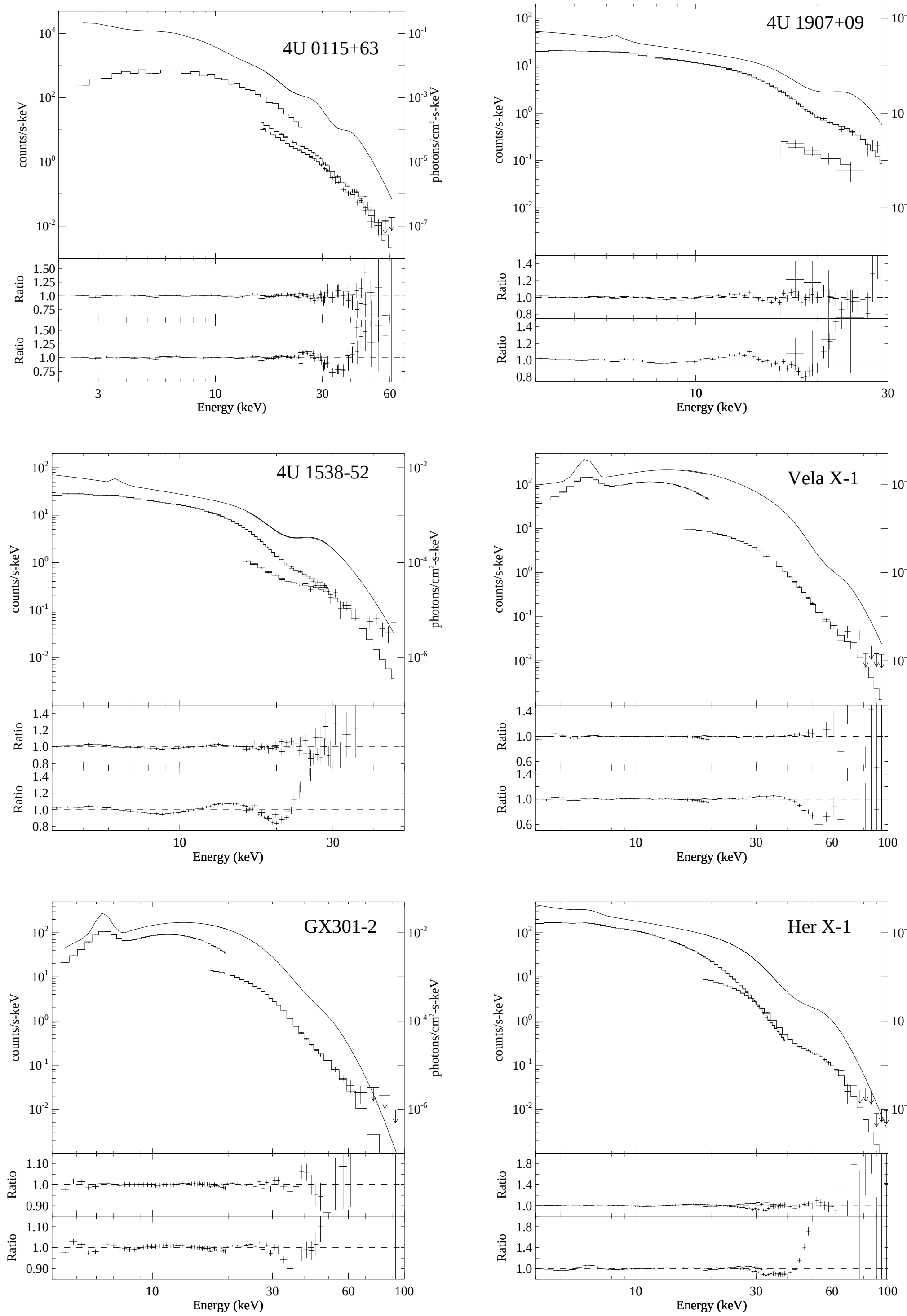

FIGURE 2. *RXTE* spectra of six accreting pulsars. Top panels show inferred incident spectra (solid lines) and PCA and HEXTE counts spectra. Middle panels show the ratio of the best fit model, which includes a CRSF, to the data. Bottom panels show this ratio for a model which has no CRSF. In the case of 4U 0115+63, which has three lines in this spectrum, we show residuals to models with three and two lines included. For line parameters, see Table 1.

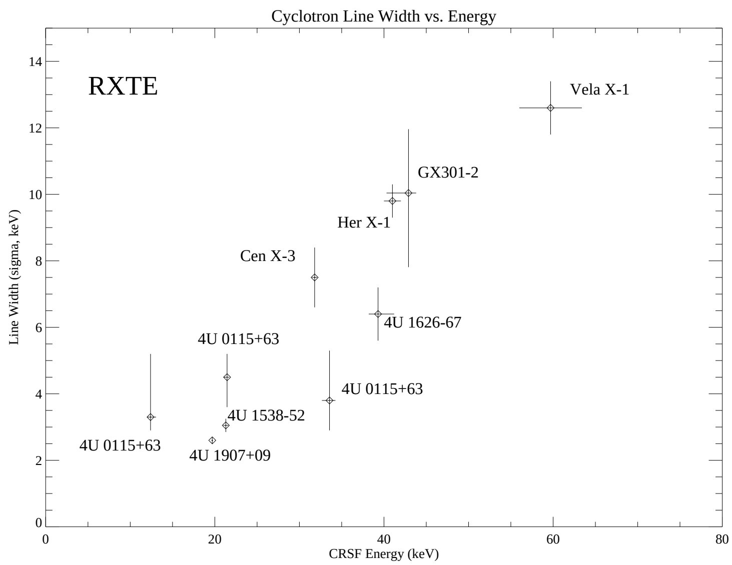

FIGURE 3. CRSF width versus line energy for all the eight pulsars discussed here. A positive correlation between energy and with is apparent. Note that for the three cyclotron lines in 4U 0115+63, the correlation does not appear to apply.